HIGH FREQUENCY COMMUNICATION SYSTEMS

Lecture 2

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- Dielectric Properties and Materials
- Nanoscale Electromagnetics

- We can extract many material properties from ε and μ.

The speed of light:

$$c = \sqrt{\frac{1}{\mu\varepsilon}}$$

The characteristic impedance:

$$\eta = \sqrt{\frac{\mu}{\varepsilon}}$$

The refractive index:

$$n = \sqrt{\mu\varepsilon}$$

- Most materials are considered non-magnetic ($\mu_r = 1$).
- Further properties at nanoscale EM

In real life, there are many types of media. Generally,

$$\vec{\mathbf{D}}(\vec{\mathbf{r}}, t) = \varepsilon(\vec{\mathbf{r}})\vec{\mathbf{E}}(\vec{\mathbf{r}}, t)[\mathrm{C\,m^{-2}}]$$

Anisotropic materials:

$$\begin{bmatrix} D_x \\ D_y \\ D_z \end{bmatrix} = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz} \end{bmatrix} \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix}$$

The permittivity ε is a tensor (or matrix) as properties depend on the direction.

For media with loss, ε is a complex number.

- For dispersive media, $\varepsilon = f(\omega)$.
  - Unsuitable for communications
    - Material Dispersion causes pulse spreading
- We compute the dispersion relation for devices such as waveguides.
- However, naturally all materials are dispersive to some extent.

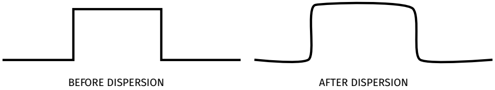


Figure 1: Frequency Dispersion

- Common circuit laws (Ohm's, KCL, and KVL) can be derived from the Maxwell's equations
- All circuit relations can be extracted

$$\vec{\mathbf{J}}_c = \sigma \vec{\mathbf{E}} \quad \Leftrightarrow \quad i = \frac{1}{R} v_R = G v_R \qquad \text{(Ohm's Law)}$$

$$\vec{\mathbf{B}} = \mu \vec{\mathbf{H}} \quad \Leftrightarrow \quad \phi_m = L i_L$$

$$\vec{\mathbf{M}} = \mu \frac{\partial \vec{\mathbf{H}}}{\partial t} \quad \Leftrightarrow \quad v_L = L \frac{\partial i_L}{\partial t}$$

$$\vec{\mathbf{D}} = \varepsilon \vec{\mathbf{E}} \quad \Leftrightarrow \quad Q = C v$$

$$\vec{\mathbf{J}}_d = \varepsilon \frac{\partial \vec{\mathbf{E}}}{\partial t} \quad \Leftrightarrow \quad i_C = C \frac{\partial v}{\partial t}$$

$$\oint_C \vec{\mathbf{E}} \cdot \mathrm{d}\vec{\mathbf{l}} = -\frac{\partial}{\partial t} \iint_S \vec{\mathbf{B}} \cdot \mathrm{d}\vec{\mathbf{S}} = -\frac{\partial \phi_m}{\partial t} \Leftrightarrow \sum v = -\frac{\partial \phi_m}{\partial t} = -L_s \frac{\partial i}{\partial t}$$

$$-V + V_R + V_L + V_C = -L_s \frac{\partial i}{\partial t}$$

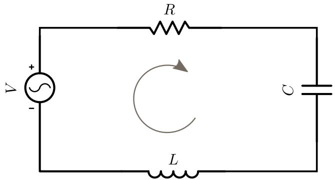


Figure 2: A Simple Circuit

- $L_s = 0$ when circuit dimensions are much smaller than the wavelength ($\implies \sum v = 0$).

Circuit	Field
Voltage V	Electric Field Intensity $\vec{\mathbf{E}}$
Current I	Magnetic Field Intensity $\vec{\mathbf{H}}$
Power $V \times I^*$	Poynting Vector Power Flow $\vec{\mathbf{E}} \times \vec{\mathbf{H}}^*$

You may have noticed loss of cell-phone reception when inside an elevator or driving through a tunnel.

EM wave propagation is governed by boundary conditions.

- We are interested in determining the fields in a given region in space
  - Use the integral forms to derive the boundary conditions
- Boundaries represent discontinuities in field values
  - The derivatives become undefined
- We break the fields into *tangential* and *normal* components

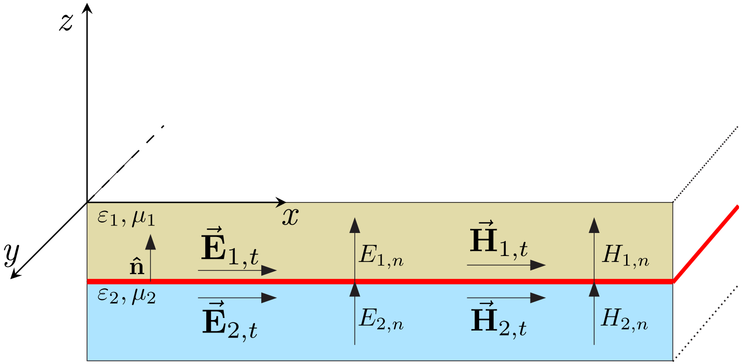


Figure 3: Boundary Conditions at an Interface

- The tangential components of the fields remain continuous along the boundary
- The normal components are discontinuous

$$\hat{\mathbf{n}} \times (\vec{\mathbf{E}}_1 - \vec{\mathbf{E}}_2) = \vec{\mathbf{M}}_s$$
$$\hat{\mathbf{n}} \cdot (\vec{\mathbf{D}}_2 - \vec{\mathbf{D}}_1) = \rho_{e,s}$$

Similarly,

$$\hat{\mathbf{n}} \times (\vec{\mathbf{H}}_1 - \vec{\mathbf{H}}_2) = -\vec{\mathbf{J}}_s$$
$$\hat{\mathbf{n}} \cdot (\vec{\mathbf{B}}_2 - \vec{\mathbf{B}}_1) = \rho_{m,s}$$

- For finite conductivity media $(\sigma_1, \sigma_2 \neq \infty)$
  - $\vec{\mathbf{J}}_s, \vec{\mathbf{M}}_s = 0$, $\rho_{e,s}, \rho_{m,s} = 0$

$$
\begin{aligned}
\widehat{\mathbf{n}} \times (\vec{\mathbf{E}}_1 - \vec{\mathbf{E}}_2) &= 0 \\
\widehat{\mathbf{n}} \times (\vec{\mathbf{H}}_2 - \vec{\mathbf{H}}_1) &= 0 \\
\widehat{\mathbf{n}} \cdot (\vec{\mathbf{D}}_2 - \vec{\mathbf{D}}_1) &= 0 \\
\widehat{\mathbf{n}} \cdot (\vec{\mathbf{B}}_2 - \vec{\mathbf{B}}_1) &= 0
\end{aligned}
$$

- For one PEC medium ($\sigma_1 = \infty$)
  - $\vec{\mathbf{E}_1} = \vec{\mathbf{H}_1} = 0$, All magnetic sources are zero

$$\widehat{\mathbf{n}} \times \vec{\mathbf{E}}_2 = 0$$
$$\widehat{\mathbf{n}} \cdot \vec{\mathbf{H}}_2 = \vec{\mathbf{J}}_s$$
$$\widehat{\mathbf{n}} \cdot \vec{\mathbf{D}} = \rho_{e,s}$$
$$\widehat{\mathbf{n}} \cdot \vec{\mathbf{B}}_2 = 0$$

- In majority of cases, the time-variance of the fields is sinusoidal (time-harmonic).
- These time variations represented by $\exp(j\omega t)$
- We replace $\partial/\partial t$ by $j\omega$.

$$
\begin{aligned}
\boldsymbol{\nabla} \times \vec{\mathbf{E}} &= -j\omega\vec{\mathbf{B}} \\
\boldsymbol{\nabla} \times \vec{\mathbf{H}} &= j\omega\varepsilon\vec{\mathbf{E}} + \vec{\mathbf{J}} \\
\boldsymbol{\nabla} \cdot \vec{\mathbf{E}} &= \rho/\varepsilon \\
\boldsymbol{\nabla} \cdot \vec{\mathbf{H}} &= 0
\end{aligned}
$$

- Maxwell's Equations are first-order partial differential equations
  - They are coupled equations (i.e. the unknown $\vec{\mathbf{E}}$ and $\vec{\mathbf{H}}$) appear in each equation
- To find the solution of the equations we treat it as a boundary value problem
- We also uncouple the equations by raising the order (*here two*).
- The result is the *wave equation*.

Recall,

$$\nabla \times \vec{\mathbf{E}} = -\mu\frac{\partial \vec{\mathbf{H}}}{\partial t} - \vec{\mathbf{M}} \qquad \text{(Faraday's Law)}$$

$$\nabla \times \vec{\mathbf{H}} = \frac{\partial \vec{\mathbf{D}}}{\partial t} + \vec{\mathbf{J}} \qquad \text{(Ampere's Law)}$$

where,

$$\vec{\mathbf{J}} = \vec{\mathbf{J}}_i + \sigma\vec{\mathbf{E}}$$

We take the curl of the above two equations and use the vector identity, $\nabla \times \nabla \times \vec{\mathbf{A}} \equiv \nabla(\nabla \cdot \vec{\mathbf{A}}) - \nabla^2\vec{\mathbf{A}}$,

$$\nabla(\nabla \cdot \vec{\mathbf{E}}) - \nabla^2\vec{\mathbf{E}} = -\nabla \times \vec{\mathbf{M}} - \mu\frac{\partial}{\partial t}\left(\nabla \times \vec{\mathbf{H}}\right)$$

$$\nabla(\rho_s/\varepsilon) - \nabla^2\vec{\mathbf{E}} = -\nabla \times \vec{\mathbf{M}} - \mu\frac{\partial \vec{\mathbf{J}}_i}{\partial t} - \mu\sigma\frac{\partial \vec{\mathbf{E}}}{\partial t} - \mu\varepsilon\frac{\partial^2 \vec{\mathbf{E}}}{\partial t^2}$$

After rearranging we get the *uncoupled* second-order differential equation for $\vec{\mathbf{E}}$,

$$\nabla^2\vec{\mathbf{E}} = \boldsymbol{\nabla} \times \vec{\mathbf{M}}_i + \mu\frac{\partial \vec{\mathbf{J}}_i}{\partial t} + \mu\sigma\frac{\partial \vec{\mathbf{E}}}{\partial t} + \mu\varepsilon\frac{\partial^2 \vec{\mathbf{E}}}{\partial t^2} + \frac{1}{\varepsilon}\boldsymbol{\nabla}\rho_s$$

- Simplest electromagnetic wave
- Generally propagate in a fixed direction (e.g. z)
- The EM fields are only functions of time and space coordinate z.
- No variation in transverse coordinates ($\frac{\partial}{\partial x}, \frac{\partial}{\partial y} = 0$)
  - $E_z = H_z = 0$

$$\vec{\mathbf{E}}(x, y, z, t) = \vec{\mathbf{E}}(z, t)$$

For a uniform plane wave, the source-free Maxwell's equations are:

$$\nabla \times \vec{\mathbf{E}} = -\frac{\partial \vec{\mathbf{B}}}{\partial t} \implies \hat{\mathbf{z}} \times \frac{\partial \vec{\mathbf{E}}}{\partial z} = -\frac{\partial \vec{\mathbf{B}}}{\partial t}$$

$$\nabla \times \vec{\mathbf{H}} = \frac{\partial \vec{\mathbf{D}}}{\partial t} \implies \hat{\mathbf{z}} \times \frac{\partial \vec{\mathbf{H}}}{\partial z} = \frac{\partial \vec{\mathbf{D}}}{\partial t}$$

$$\nabla \cdot \vec{\mathbf{E}} = 0 \implies \frac{\partial E_z}{\partial z} = 0$$

$$\nabla \cdot \vec{\mathbf{H}} = 0 \implies \frac{\partial H_z}{\partial z} = 0$$

- Starting with a uniform plane wave in a source-free region.
- Considering one-dimensional case
- Since $E_z, H_z = 0$, we start with and use the identity $(\widehat{\mathbf{z}} \cdot (\widehat{\mathbf{z}} \times \vec{\mathbf{A}}) \equiv 0)$:

$$\widehat{\mathbf{z}} \cdot \left(\widehat{\mathbf{z}} \times \frac{\partial \vec{\mathbf{H}}}{\partial z} \right) = \varepsilon \frac{\partial \vec{\mathbf{E}}}{\partial t} = 0 \implies \frac{\partial E_z}{\partial t} = 0$$

The solutions (transverse fields) must be of the form:

$$\vec{\mathbf{E}}(z,t) = \widehat{\mathbf{x}} E_x(z,t) + \widehat{\mathbf{y}} E_y(z,t)$$
$$\vec{\mathbf{H}}(z,t) = \widehat{\mathbf{x}} H_x(z,t) + \widehat{\mathbf{y}} H_y(z,t)$$

The electric and magnetic fields only exist in the $x-y$ plane which is perpendicular to the direction of propagation.

- We can also simplify 1D Maxwell's equations

$$\widehat{\mathbf{z}} \times \frac{\partial \vec{\mathbf{E}}}{\partial z} = -\frac{1}{c}\eta\frac{\partial \vec{\mathbf{H}}}{\partial t}$$
$$\eta\widehat{\mathbf{z}} \times \frac{\partial \vec{\mathbf{H}}}{\partial z} = -\frac{1}{c}\frac{\partial \vec{\mathbf{E}}}{\partial t}$$

where,

$$c = \frac{1}{\sqrt{\mu\varepsilon}}, and \eta = \sqrt{\frac{\mu}{\varepsilon}}$$

Using the BAC-CAB ($\vec{\mathbf{A}} \times (\vec{\mathbf{B}} \times \vec{\mathbf{C}}) = \vec{\mathbf{B}}(\vec{\mathbf{A}} \cdot \vec{\mathbf{C}}) - (\vec{\mathbf{B}} \cdot \vec{\mathbf{A}})\vec{\mathbf{C}}$) rule of vector algebra:

$$\left(\widehat{\mathbf{z}} \times \frac{\partial \vec{\mathbf{E}}}{\partial z}\right) \times \widehat{\mathbf{z}} = \frac{\partial \vec{\mathbf{E}}}{\partial z} - \widehat{\mathbf{z}}\left(\widehat{\mathbf{z}} \cdot \frac{\partial \vec{\mathbf{E}}}{\partial z}\right) = \frac{\partial \vec{\mathbf{E}}}{\partial z}$$

We can now write the Maxwell's equations as:

$$\frac{\partial \vec{\mathbf{E}}}{\partial z} = -\frac{1}{c}\frac{\partial}{\partial t}\left(\eta \vec{\mathbf{H}} \times \widehat{\mathbf{z}}\right)$$

$$\frac{\partial}{\partial z}\left(\eta \vec{\mathbf{H}} \times \widehat{\mathbf{z}}\right) = -\frac{1}{c}\frac{\partial \vec{\mathbf{E}}}{\partial t}$$

We differentiate the first equation w.r.t z and use the second:

$$\frac{\partial^2 \vec{\mathbf{E}}}{\partial z^2} = -\frac{1}{c}\frac{\partial^2}{\partial t \partial z}\left(\eta \vec{\mathbf{H}} \times \widehat{\mathbf{z}}\right) = \frac{1}{c^2}\frac{\partial^2 \vec{\mathbf{E}}}{\partial t^2}$$

which is the 1D wave equation. We can also write in a convenient form as:

$$\boxed{\left(\frac{\partial^2}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\vec{\mathbf{E}}(z,t) = 0}$$

- Time-harmonic representation $\exp(j\omega t)$ is convenient in finding the solutions
- We replace the derivatives $\frac{\partial}{\partial t}$ and $\frac{\partial^2}{\partial t^2}$ by $j\omega$ and $-\omega^2$ respectively
- We also call the result as the Helmholtz equation.
- For source-free ($\vec{\mathbf{J}} = \vec{\mathbf{M}} = 0$) case, we get

$$\nabla^2\vec{\mathbf{E}} + \omega^2\mu\varepsilon\vec{\mathbf{E}} = 0$$

$$\nabla^2\vec{\mathbf{E}} + \beta^2\vec{\mathbf{E}} = 0$$

- A second order differential equation leads to 2 solutions
  - We can split the fields into *forward* and *backward* components.
- We use the *Separation of variables* method to obtain the solutions of vector wave equation
  - By solving the scalar equations for each components

$$\vec{\mathbf{E}} = \widehat{\mathbf{x}}E_x + \widehat{\mathbf{y}}E_y + \widehat{\mathbf{z}}E_z$$

As an example, for the x-component, we get:

$$\nabla^2 E_x(x, y, z) + \beta^2 E_x(x, y, z) = 0$$

The solution is of the form:

$$E_x(x, y, z) = f(x)g(y)h(z)$$

- There are different forms of solutions we can use
  - Depends on the nature of the problem
- For free-space problems, we use the travelling wave form

$$h(z) = A_1 \exp\left(-j\beta_z z\right) + B_1 \exp\left(+j\beta_z z\right)$$

For confined problems (such as a waveguide), we use the standing wave form:

$$g(x) = A_2 \sin(\beta_y y) + B_2 \cos(\beta_y y)$$

- Uniform travelling wave in the $+z$ direction
- Equiphase plane (increase in t also increase z)

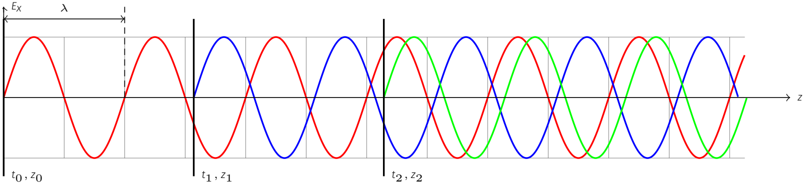


Figure 4: X-polarized Plane Wave propagation along z direction

For the above, the plane wave can be described as:

$$E_x(z,t) = \cos(\omega t - \beta z)$$

MATERIAL PROPERTIES

- Materials play a huge role in electromagnetic radiation and guiding
- The electrons inside the atom of a material behave differently when an external electric field is applied
  - The electric field distorts the electron distribution
  - An electric dipole moment is created
- We tend to observe it macroscopically (not at the atom level but over the volume of the material)
- We need to describe the behaviour of ε with frequency (using Classical Harmonic model)

$$\frac{\mathrm{d}^2 x}{\mathrm{d}t^2} + \gamma \frac{\mathrm{d}x}{\mathrm{d}t} + \omega_0^2 x = \frac{e}{m} E$$

where γ is a measure of rate of collisions per unit time, ω_0 refers to the resonant frequency, e and m are the electron charge and mass respectively.

- Using the phaser form of the Harmonic model for a plane wave, $E(t) = E_0 \exp(j\omega t)$

$$\varepsilon(\omega) = \varepsilon_0 + \frac{\varepsilon_0 + \omega_p^2}{\omega_0^2 - \omega^2 + j\omega\gamma} \qquad \text{(Lorentz Model)}$$

where ε_0 is the free-space permittivity, ω_p is the plasma frequency given by:

$$\omega_p = \sqrt{\frac{Ne^2}{\varepsilon_0 m}}$$

N being the charge density.

- The real part of ε refers to the refractive properties
- The imaginary part determines the absorption or loss.

- Formation of electric dipoles in the presence of external electric fields.
- There are magnetic materials as well but we are not interested in them in this course.
  - We assume $\mu_r = 1$ for all materials.

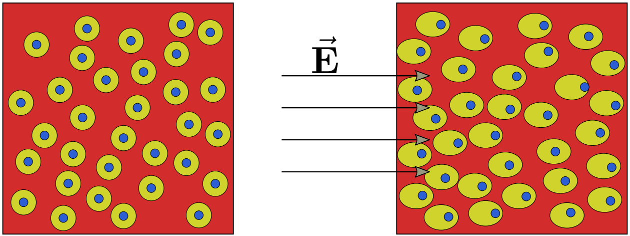


Figure 5: Effect of electric field on dipole formation.

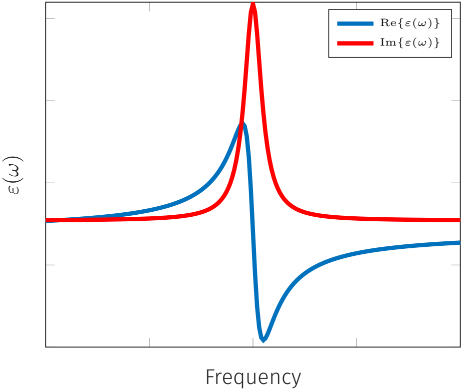


Figure 6: The dielectric function using the Lorentz Model

- Main difference from dielectrics is that the motion of electric charges and the generation of current flow.
- Conductors have *loosely held* electrons in the valence band of atoms [free electrons]
- Conductors have very high values of electric conductivity ($\sigma \to \infty$).
- For perfect electric conductors, we use $\sigma = \infty$.

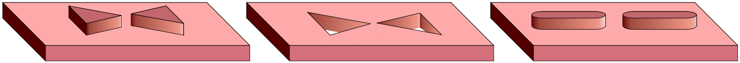
$$\varepsilon(\omega) = \varepsilon_0 + \frac{\sigma(\omega)}{j\omega} \qquad \text{(Drude Model)}$$

- Plasma like solid, liquid and gas is the fourth form of matter
- We consider the resonant frequency $\omega_0 = 0$.
- Plasma effectively acts as a switch
  - Before plasma frequency, wave is completely attenuated.
  - After ω_p, there is zero attenuation

$$\varepsilon(\omega) = \varepsilon_0 + \left(1 - \frac{\omega_p^2}{\omega^2}\right)$$

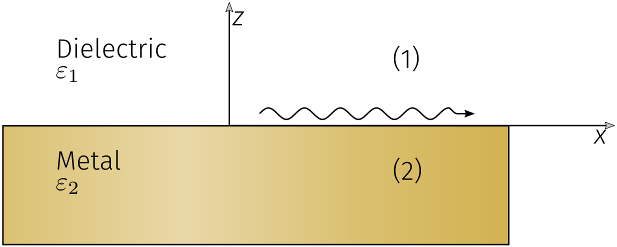
NANOSCALE ELECTROMAGNETICS

- Electronic device sizes are fast approaching the nanoscale
  - Modern transistors are typically 5 nm in size
- Maxwell's equations have remained valid at macro scale
  - However, discrepancies have lately surfaced at the nanoscale level between the theory and experiment
- Highlight of nanoscale electromagnetics is the *complex-valued* nature of the relative permittivity
- Interestingly, EM surface waves exist at metal/dielectric interfaces



- EM fields can be split into *transverse-magnetic* (TM) and *transverse-electric* (TE) components
- Observing a planar dielectric-metal interface, TM-mode means H-field only has a transverse (H_y) component
  - The E-field has E_x and E_z components

- At optical and mid infrared frequencies ($> 10\,\mathrm{THz}$), some materials such as gold exhibit negative dielectric constant $(\mathrm{Re}(\varepsilon_r) < 0)$
- At a metal-dielectric interface such as the one below:



- The TM mode fields in region 1 are expressed as:

$$\vec{\mathbf{E}}_1 = (\widehat{\mathbf{x}} E_{x1} + \widehat{\mathbf{z}} E_{z1}) \exp\left(-j(k_x x + k_{z1} z)\right),$$
$$\vec{\mathbf{H}}_1 = \widehat{\mathbf{y}} H_{y1} \exp\left(-j(k_x x + k_{z1} z)\right)$$

and likewise for region 2. Using the Ampere's Law ($\boldsymbol{\nabla} \times \vec{\mathbf{H}} = -j\omega \vec{\mathbf{E}}$), we get the boundary conditions:

$$k_{z1} H_{y1} = \omega \varepsilon_1 E_{x1}$$
$$k_{z2} H_{y2} = -\omega \varepsilon_2 E_{x2}$$

- Ensuring the continuity of tangential fields, $E_{x1} = E_{x2}$ and $H_{y1} = H_{y2}$, we get:

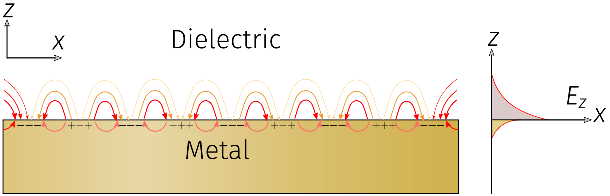
$$\frac{k_{z1}}{\varepsilon_1} + \frac{k_{z2}}{\varepsilon_2} = 0.$$

- Using the Helmholtz equation, $\left(\nabla^2 \vec{\mathbf{E}} + k_i^2 \vec{\mathbf{E}} = 0\right)$, where $i = 1, 2$, and assuming the permeabilities of all regions are that of air, we obtain,

$$k_x = k_0 \sqrt{\frac{\varepsilon_{r1}\varepsilon_{r2}}{\varepsilon_{r1} + \varepsilon_{r2}}}$$

- The dispersion relation has a solution when

$$\varepsilon_1 > 0, \quad \varepsilon_2' < 0, \quad \text{and} \quad |\varepsilon_2'| > \varepsilon_1,$$



Surface plasmon propagation along a dielectric-metal boundary and exponential decay perpendicular to the boundary.

LECTURE OUTLINE

- Plane waves and the wave equation
- Dielectric Properties and Materials
- Nanoscale Electromagnetics

- Maxwell's Equations are first-order partial differential equations
  - They are coupled equations (i.e. the unknown $\vec{\mathbf{E}}$ and $\vec{\mathbf{H}}$) appear in each equation
- To find the solution of the equations we treat it as a boundary value problem
- We also uncouple the equations by raising the order (*here two*).
- The result is the *wave equation*.

Recall,

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$$\boldsymbol{\nabla} \times \vec{\mathbf{H}} = \frac{\partial \vec{\mathbf{D}}}{\partial t} + \vec{\mathbf{J}} \qquad \text{(Ampere's Law)}$$

where,

$$\vec{\mathbf{J}} = \vec{\mathbf{J}}_i + \sigma \vec{\mathbf{E}}$$

We take the curl of the above two equations and use the vector identity, $\boldsymbol{\nabla} \times \boldsymbol{\nabla} \times \vec{\mathbf{A}} \equiv \boldsymbol{\nabla}(\boldsymbol{\nabla} \cdot \vec{\mathbf{A}}) - \nabla^2 \vec{\mathbf{A}}$,

$$\boldsymbol{\nabla}(\boldsymbol{\nabla} \cdot \vec{\mathbf{E}}) - \nabla^2 \vec{\mathbf{E}} = -\boldsymbol{\nabla} \times \vec{\mathbf{M}} - \mu \frac{\partial}{\partial t}\left(\boldsymbol{\nabla} \times \vec{\mathbf{H}}\right)$$

$$\boldsymbol{\nabla}(\rho_s/\varepsilon) - \nabla^2 \vec{\mathbf{E}} = -\boldsymbol{\nabla} \times \vec{\mathbf{M}} - \mu \frac{\partial \vec{\mathbf{J}}_i}{\partial t} - \mu\sigma \frac{\partial \vec{\mathbf{E}}}{\partial t} - \mu\varepsilon \frac{\partial^2 \vec{\mathbf{E}}}{\partial t^2}$$

After rearranging we get the *uncoupled* second-order differential equation for $\vec{\mathbf{E}}$,

$$\nabla^2\vec{\mathbf{E}} = \boldsymbol{\nabla} \times \vec{\mathbf{M}}_i + \mu\frac{\partial\vec{\mathbf{J}}_i}{\partial t} + \mu\sigma\frac{\partial\vec{\mathbf{E}}}{\partial t} + \mu\varepsilon\frac{\partial^2\vec{\mathbf{E}}}{\partial t^2} + \frac{1}{\varepsilon}\boldsymbol{\nabla}\rho_s$$

- Simplest electromagnetic wave
- Generally propagate in a fixed direction (e.g. z)
- The EM fields are only functions of time and space coordinate z.
- No variation in transverse coordinates ($\frac{\partial}{\partial x}, \frac{\partial}{\partial y} = 0$)
  - $E_z = H_z = 0$

$$\vec{\mathbf{E}}(x, y, z, t) = \vec{\mathbf{E}}(z, t)$$

For a uniform plane wave, the source-free Maxwell's equations are:

$$\nabla \times \vec{\mathbf{E}} = -\frac{\partial \vec{\mathbf{B}}}{\partial t} \implies \widehat{\mathbf{z}} \times \frac{\partial \vec{\mathbf{E}}}{\partial z} = -\frac{\partial \vec{\mathbf{B}}}{\partial t}$$

$$\nabla \times \vec{\mathbf{H}} = \frac{\partial \vec{\mathbf{D}}}{\partial t} \implies \widehat{\mathbf{z}} \times \frac{\partial \vec{\mathbf{H}}}{\partial z} = \frac{\partial \vec{\mathbf{D}}}{\partial t}$$

$$\nabla \cdot \vec{\mathbf{E}} = 0 \implies \frac{\partial E_z}{\partial z} = 0$$

$$\nabla \cdot \vec{\mathbf{H}} = 0 \implies \frac{\partial H_z}{\partial z} = 0$$

- Starting with a uniform plane wave in a source-free region.
- Considering one-dimensional case
- Since $E_z, H_z = 0$, we start with and use the identity ($\widehat{\mathbf{z}} \cdot (\widehat{\mathbf{z}} \times \vec{\mathbf{A}}) \equiv 0$):

$$\widehat{\mathbf{z}} \cdot \left(\widehat{\mathbf{z}} \times \frac{\partial \vec{\mathbf{H}}}{\partial z}\right) = \varepsilon \frac{\partial \vec{\mathbf{E}}}{\partial t} = 0 \implies \frac{\partial E_z}{\partial t} = 0$$

The solutions (transverse fields) must be of the form:

$$\vec{\mathbf{E}}(z,t) = \widehat{\mathbf{x}} E_x(z,t) + \widehat{\mathbf{y}} E_y(z,t)$$
$$\vec{\mathbf{H}}(z,t) = \widehat{\mathbf{x}} H_x(z,t) + \widehat{\mathbf{y}} H_y(z,t)$$

The electric and magnetic fields only exist in the $x - y$ plane which is perpendicular to the direction of propagation.

- We can also simplify 1D Maxwell's equations

$$\widehat{\mathbf{z}} \times \frac{\partial \vec{\mathbf{E}}}{\partial z} = -\frac{1}{c}\eta\frac{\partial \vec{\mathbf{H}}}{\partial t}$$
$$\eta\widehat{\mathbf{z}} \times \frac{\partial \vec{\mathbf{H}}}{\partial z} = -\frac{1}{c}\frac{\partial \vec{\mathbf{E}}}{\partial t}$$

where,

$$c = \frac{1}{\sqrt{\mu\varepsilon}}, and \eta = \sqrt{\frac{\mu}{\varepsilon}}$$

Using the BAC-CAB ($\vec{\mathbf{A}} \times (\vec{\mathbf{B}} \times \vec{\mathbf{C}}) = \vec{\mathbf{B}}(\vec{\mathbf{A}} \cdot \vec{\mathbf{C}}) - (\vec{\mathbf{B}} \cdot \vec{\mathbf{A}})\vec{\mathbf{C}}$) rule of vector algebra:

$$\left(\widehat{\mathbf{z}} \times \frac{\partial \vec{\mathbf{E}}}{\partial z}\right) \times \widehat{\mathbf{z}} = \frac{\partial \vec{\mathbf{E}}}{\partial z} - \widehat{\mathbf{z}}\left(\widehat{\mathbf{z}} \cdot \frac{\partial \vec{\mathbf{E}}}{\partial z}\right) = \frac{\partial \vec{\mathbf{E}}}{\partial z}$$

We can now write the Maxwell's equations as:

$$\frac{\partial \vec{\mathbf{E}}}{\partial z} = -\frac{1}{c}\frac{\partial}{\partial t}\left(\eta \vec{\mathbf{H}} \times \hat{\mathbf{z}}\right)$$

$$\frac{\partial}{\partial z}\left(\eta \vec{\mathbf{H}} \times \hat{\mathbf{z}}\right) = -\frac{1}{c}\frac{\partial \vec{\mathbf{E}}}{\partial t}$$

We differentiate the first equation w.r.t z and use the second:

$$\frac{\partial^2 \vec{\mathbf{E}}}{\partial z^2} = -\frac{1}{c}\frac{\partial^2}{\partial t \partial z}\left(\eta \vec{\mathbf{H}} \times \hat{\mathbf{z}}\right) = \frac{1}{c^2}\frac{\partial^2 \vec{\mathbf{E}}}{\partial t^2}$$

which is the 1D wave equation. We can also write in a convenient form as:

$$\left(\frac{\partial^2}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\vec{\mathbf{E}}(z,t) = 0$$

- Time-harmonic representation $\exp(j\omega t)$ is convenient in finding the solutions
- We replace the derivatives $\frac{\partial}{\partial t}$ and $\frac{\partial^2}{\partial t^2}$ by $j\omega$ and $-\omega^2$ respectively
- We also call the result as the Helmholtz equation.
- For source-free ($\vec{\mathbf{J}} = \vec{\mathbf{M}} = 0$) case, we get

$$\nabla^2 \vec{\mathbf{E}} + \omega^2 \mu \varepsilon \vec{\mathbf{E}} = 0$$
$$\nabla^2 \vec{\mathbf{E}} + \beta^2 \vec{\mathbf{E}} = 0$$

- A second order differential equation leads to 2 solutions
  - We can split the fields into *forward* and *backward* components.
- We use the *Separation of variables* method to obtain the solutions of vector wave equation
  - By solving the scalar equations for each components

$$\vec{\mathbf{E}} = \widehat{\mathbf{x}} E_x + \widehat{\mathbf{y}} E_y + \widehat{\mathbf{z}} E_z$$

As an example, for the x-component, we get:

$$\nabla^2 E_x(x, y, z) + \beta^2 E_x(x, y, z) = 0$$

The solution is of the form:

$$E_x(x, y, z) = f(x)g(y)h(z)$$

- There are different forms of solutions we can use
  - Depends on the nature of the problem
- For free-space problems, we use the travelling wave form

$$h(z) = A_1 \exp\left(-j\beta_z z\right) + B_1 \exp\left(+j\beta_z z\right)$$

For confined problems (such as a waveguide), we use the standing wave form:

$$g(x) = A_2 \sin(\beta_y y) + B_2 \cos(\beta_y y)$$

- Uniform travelling wave in the $+z$ direction
- Equiphase plane (increase in t also increase z)

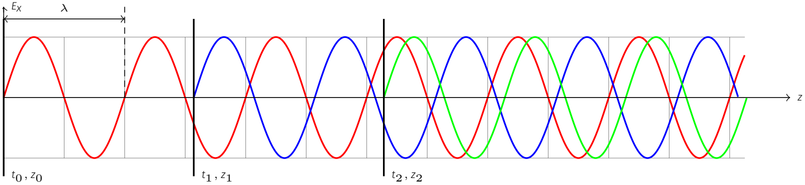


Figure 7: X-polarized Plane Wave propagation along z direction

For the above, the plane wave can be described as:

$$E_x(z, t) = \cos(\omega t - \beta z)$$

MATERIAL PROPERTIES

- Materials play a huge role in electromagnetic radiation and guiding
- The electrons inside the atom of a material behave differently when an external electric field is applied
  - The electric field distorts the electron distribution
  - An electric dipole moment is created
- We tend to observe it macroscopically (not at the atom level but over the volume of the material)
- We need to describe the behaviour of ε with frequency (using Classical Harmonic model)

$$\frac{\mathrm{d}^2 x}{\mathrm{d}t^2} + \gamma \frac{\mathrm{d}x}{\mathrm{d}t} + \omega_0^2 x = \frac{e}{m} E$$

where γ is a measure of rate of collisions per unit time, ω_0 refers to the resonant frequency, e and m are the electron charge and mass respectively.

- Using the phaser form of the Harmonic model for a plane wave, $E(t) = E_0 \exp(j\omega t)$

$$\varepsilon(\omega) = \varepsilon_0 + \frac{\varepsilon_0 + \omega_p^2}{\omega_0^2 - \omega^2 + j\omega\gamma} \qquad \text{(Lorentz Model)}$$

where ε_0 is the free-space permittivity, ω_p is the plasma frequency given by:

$$\omega_p = \sqrt{\frac{Ne^2}{\varepsilon_0 m}}$$

N being the charge density.

- The real part of ε refers to the refractive properties
- The imaginary part determines the absorption or loss.

- Formation of electric dipoles in the presence of external electric fields.
- There are magnetic materials as well but we are not interested in them in this course.
  - We assume $\mu_r = 1$ for all materials.

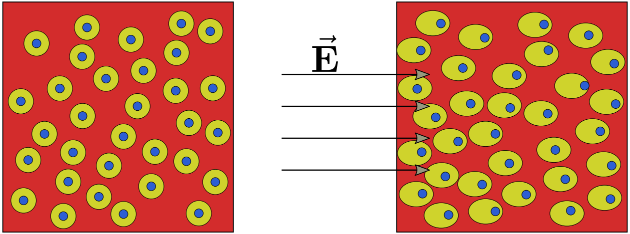


Figure 8: Effect of electric field on dipole formation.

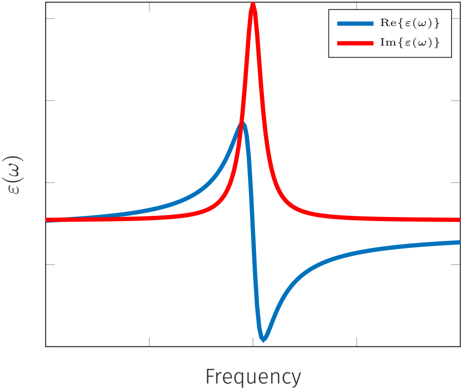


Figure 9: The dielectric function using the Lorentz Model

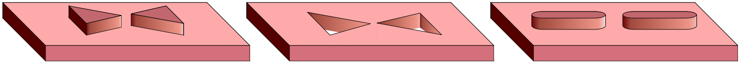
- Main difference from dielectrics is that the motion of electric charges and the generation of current flow.
- Conductors have *loosely held* electrons in the valence band of atoms [free electrons]
- Conductors have very high values of electric conductivity ($\sigma \to \infty$).
- For perfect electric conductors, we use $\sigma = \infty$.

$$\varepsilon(\omega) = \varepsilon_0 + \frac{\sigma(\omega)}{j\omega} \qquad \text{(Drude Model)}$$

- Plasma like solid, liquid and gas is the fourth form of matter
- We consider the resonant frequency $\omega_0 = 0$.
- Plasma effectively acts as a switch
  - Before plasma frequency, wave is completely attenuated.
  - After ω_p, there is zero attenuation

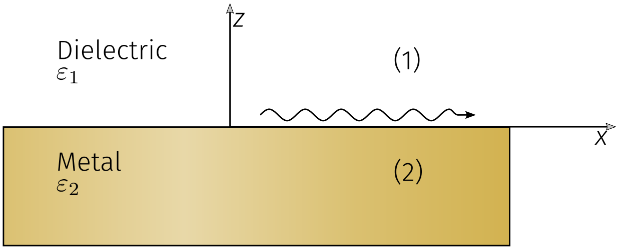
$$\varepsilon(\omega) = \varepsilon_0 + \left(1 - \frac{\omega_p^2}{\omega^2}\right)$$

- Electronic device sizes are fast approaching the nanoscale
  - Modern transistors are typically 5 nm in size
- Maxwell's equations have remained valid at macro scale
  - However, discrepancies have lately surfaced at the nanoscale level between the theory and experiment
- Highlight of nanoscale electromagnetics is the *complex-valued* nature of the relative permittivity
- Interestingly, EM surface waves exist at metal/dielectric interfaces



- EM fields can be split into *transverse-magnetic* (TM) and *transverse-electric* (TE) components
- Observing a planar dielectric-metal interface, TM-mode means H-field only has a transverse (H_y) component
  - The E-field has E_x and E_z components

- At optical and mid infrared frequencies ($> 10\,\mathrm{THz}$), some materials such as gold exhibit negative dielectric constant $(\mathrm{Re}(\varepsilon_r) < 0)$
- At a metal-dielectric interface such as the one below:



- The TM mode fields in region 1 are expressed as:

$$\vec{\mathbf{E}}_1 = (\widehat{\mathbf{x}}E_{x1} + \widehat{\mathbf{z}}E_{z1}) \exp(-j(k_x x + k_{z1} z)),$$
$$\vec{\mathbf{H}}_1 = \widehat{\mathbf{y}}H_{y1} \exp(-j(k_x x + k_{z1} z))$$

and likewise for region 2. Using the Ampere's Law ($\nabla \times \vec{\mathbf{H}} = -j\omega\vec{\mathbf{E}}$), we get the boundary conditions:

$$k_{z1}H_{y1} = \omega\varepsilon_1 E_{x1}$$
$$k_{z2}H_{y2} = -\omega\varepsilon_2 E_{x2}$$

- Ensuring the continuity of tangential fields, $E_{x1} = E_{x2}$ and $H_{y1} = H_{y2}$, we get:

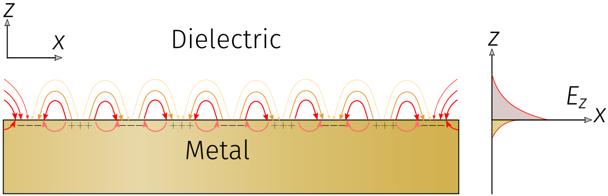
$$\frac{k_{z1}}{\varepsilon_1} + \frac{k_{z2}}{\varepsilon_2} = 0.$$

- Using the Helmholtz equation, $\left(\nabla^2 \vec{\mathbf{E}} + k_i^2 \vec{\mathbf{E}} = 0\right)$, where $i = 1, 2$, and assuming the permeabilities of all regions are that of air, we obtain,

$$k_x = k_0 \sqrt{\frac{\varepsilon_{r1}\varepsilon_{r2}}{\varepsilon_{r1} + \varepsilon_{r2}}}$$

- The dispersion relation has a solution when

$$\varepsilon_1 > 0, \quad \varepsilon_2' < 0, \quad \text{and} \quad |\varepsilon_2'| > \varepsilon_1,$$



Surface plasmon propagation along a dielectric-metal boundary and exponential decay perpendicular to the boundary.